Perspective
Greenhouse gas mitigation by covers on livestock slurry tanks and lagoons?

Liquid manure (slurry) storage facilities are important point sources of atmospheric pollution. Being point sources, containment of gaseous emissions via improved storage conditions may be possible, and permeable surface covers (natural crusts and artificial covers) are increasingly recognized for their capacity to reduce various gaseous emissions. Microbial transformations in permeable surface covers include bacterial methane oxidation, but this interface between nitrogen-rich slurry and the atmosphere is also an environment with intense nitrogen turnover that can lead to nitrous oxide emissions. Both methane and nitrous oxide are greenhouse gases, and strategies to reduce environmental impact of slurry stores must consider the total greenhouse gas balance. In this paper, greenhouse gas mitigation options for manure storages are discussed with reference mainly to practical storage conditions in Europe and North America.

ENVIRONMENTAL IMPACTS OF LIVESTOCK PRODUCTION

Large-scale confined animal feeding operations (CAFO) reflect the intensification and, indeed, industrialization, of modern livestock production. The resulting high concentrations of livestock manure pose a threat to the local environment in the form of nutrient leaching, dispersal of pathogens, ammonia deposition and odour emissions. To a large extent, environmental regulations of manure management aim to reduce health hazards and nuisances for local residents, or to prevent local and regional eutrophication of natural habitats. For example, according to a Council Directive to protect waters against pollution from agricultural sources, countries of the European Union need to adopt codes of good practice with respect to manure storage capacity, application rates and timing of application to ensure that nutrient overload of soils is avoided.[1] Similarly, in the United States, the EPA (Environmental Protection Agency), state regulatory agencies, and local communities seek to limit the potential for water pollution through regulation (i.e., the Clean Water Act), permitting, and zoning. Recently, specific CAFO guidelines have been proposed by the EPA in a Unified National Strategy for Animal Feeding Operations in order to ensure proper manure containment and application practices are followed. The US Department of Agriculture, extension specialists, and private consultants provide technical and some financial support for livestock operations to improve manure management,[2] but considerable private investment by CAFO operators is also needed in order to adopt proper manure management practices. In a case involving the state of North Carolina and corporate swine producers, Smithfield Foods and other companies agreed to fund a $17 million research effort to identify a set of Environmentally Superior Technologies to replace, in an economically viable way, swine wastewater lagoons.[3]

In addition to potential impacts on the local surface and groundwater environment, intensive livestock production emits methane and nitrous oxide to the atmosphere. These greenhouse gases (GHGs) are produced by microbes in oxygen-deficient environments and have global warming potentials on a 100-year time horizon that are 23 (methane) and 296 (nitrous oxide) times greater than that of carbon dioxide.[4] Having no short-term effects on the local environment and no direct consequences for the farm's economy, GHG emissions from agriculture have received little public attention until recently.

In 1997 a number of countries signed and later ratified the Kyoto protocol, thereby agreeing, before 2012, to reduce national GHG emissions compared with the 1990 level by a percentage negotiated for each country. Currently, many countries seek to identify GHG mitigation options, and cutting excess agricultural emissions will be important. Table 1 shows agriculture's share of total anthropogenic GHG emissions in selected countries or regions.[5] Globally, agricultural emissions of methane and nitrous oxide constitute around 25% and 80%, respectively, of all emissions from human activities. Livestock production contributes to methane emissions from ruminant digestion ($80\,\mathrm{Tg\,CH_4\,yr^{-1}}$) and animal manure ($30\,\mathrm{Tg\,CH_4\,yr^{-1}}$),[6] and to nitrous oxide emissions ($8–9\ \mathrm{Tg\ N_2O\,yr^{-1}}$) from nitrogen transformations during manure storage and after field application.[7] While feeding strategies and manure application strategies are important research areas with a potential for GHG mitigation, this paper considers GHG mitigation for slurry storages and lagoons.

The potential for methane emission from liquid manure is larger than from solid manure. This is reflected in the factors proposed in the IPCC methodology for conversion of digestible organic carbon to methane, which are 1–2% for solid storage, 39–72% for slurry storage or extended pit storage, and

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Table 1. Greenhouse gas emissions (2003) and the percentages derived from agriculture in selected countries

	Total emissions[a] (Tg CO_2 equivalents)	Contribution from agriculture (%)
United States	6900	6.3
Canada	740	8.4
European Union (25 countries)	4924	9.5
UK	651	6.9
Netherlands	215	8.2
Italy	570	6.8
Denmark	74	13.4

[a] Effects on GHG emissions (CO_2, CH_4 and N_2O) of land use, land use change and forestry (LULUCF) not included.

up to 100% for manure stored in anaerobic lagoons.[8] Emissions of nitrous oxide from liquid manure during storage are generally low. The IPCC default emission factor for this source is 0.1%, i.e., much less than the nitrous oxide emission factor for solid storage of 2%. However, a potential for nitrous oxide emission can develop in surface covers on liquid manure storages depending on ambient conditions; in one study, peak emissions corresponding to an annual loss of 0.8% of slurry nitrogen were observed during summer storage.[9] These findings indicate that GHG mitigation strategies for liquid manure storages should account for both methane and nitrous oxide when estimating the overall balance of GHG emissions.

SLURRY MANAGEMENT

The importance of liquid *versus* solid storage and, hence, the relevance of slurry tanks and lagoons as GHG sources, varies between regions and livestock categories, although intensive systems are often slurry-based. It should also be recognized that livestock slurry can vary greatly in composition depending on the production system, water use for cleaning and flushing, and whether dry matter is removed in a settling pond prior to lagoon storage.

In slurry-based production systems, the mixture of fecal matter, urine, feed spills, bedding material (if used), and cleaning water is collected under slatted floors (pit storage) for a period of days or weeks before being pumped to an outside store (slurry tank or lagoon). Deep pit storage, an alternative to lagoons in the United States, is similar to the slurry storage tank, except that the pit is contained within the production house, and manure falls into the pit from above. These environments are dominated by anaerobic conditions in which a microbial community will develop that degrades organic carbon in several steps to methane and carbon dioxide.[10] Nitrogen mineralization from urea and organic matter in urine and feces leads to high slurry ammonium concentrations which may stimulate ammonia volatilization or undergo further microbial transformations, which may include nitrous oxide formation. Methanogenesis and nitrogen mineralization are microbially controlled and strongly temperature-dependent processes. Frequent manure transfer to an outside storage with lower temperature is therefore a strategy to reduce emissions of methane and ammonia from livestock manure.[11] In a model exercise with storage conditions typical for Denmark, it was estimated that daily, as opposed to monthly, flushing of slurry channels to an outside covered storage tank could reduce total annual GHG emissions from dairy cattle manure by 35%. Collection and flaring of methane with or without energy generation is an additional GHG mitigation strategy, but one that requires investments and maintenance.

In Europe, livestock slurry is stored in 20–40 m diameter storage tanks with or (more commonly) without coverage, or in lagoons. In the United States and Canada, slurry is handled in stores (deep pits usually beneath the production house), or alternatively the slurry is diluted with water to encourage decomposition of the solids and pumped into anaerobic lagoons (2–6 m deep and up to several hectares in surface area). In some systems dilute slurry can be partly recycled to flush storage pits.[12] In both Europe and North America, livestock slurry is a valuable fertilizer and soil amendment, and thus it is subsequently applied to fields. Efforts to improve manure nutrient use efficiency by application at optimum times during the growing season has led to extended storage times. The resulting increase in environmental problems, especially from emissions of ammonia and malodorous compounds, has stimulated the interest in cover strategies. In Denmark the high level of ammonia volatilization from stored slurry prompted new legislation in 1998 making coverage of slurry tanks mandatory.

A cover may be a natural crust, which can form if the dry matter content is sufficiently high, or it may be an artificial barrier, e.g., of straw, Leca pebbles (expanded clay), a membrane, or a porous floating geotextile fabric. Alternatively, roofing made of concrete or a tent structure can be used for slurry tanks, but that is relatively costly. With the much larger surface area of lagoons, a floating cover is the only practicable solution. Permeable surface covers not only act as a physical barrier to gas transport, but there is increasing evidence that microbial communities develop in the covers, which are capable of utilizing reduced gases emitting from the slurry.

MICROBIOLOGY OF SURFACE COVERS

Permeable surface covers on livestock slurry tanks are colonized by a variety of both aerobic and anaerobic microorganisms.[13] Qualitative analyses of a permeable lagoon cover made of recycled polyethylene indicated the presence and proliferation of algae, protozoa and nematodes, as well as the presence of nitrifying, sulfur-oxidizing and methane-oxidizing bacteria.[14] Little is known about the microbiology of natural surface

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crusts. In one report, the abundance of aerobic microorganisms (assessed as colony forming units) in a natural surface crust material (0–6 cm depth) from cattle slurry stores decreased with depth in the crust.[15] However, indirect evidence concerning microbial populations and activities in surface covers may be gleaned from process studies. Methane oxidation activity was recently documented in natural surface crusts and straw covers from both pig and cattle slurry tanks.[16,17] The pathway of colonization is not known, but probably occurs from the local environment. Methanotrophic bacteria can survive for extended periods under anaerobic conditions,[18] and so initial colonization may take place before a surface crust is established. Documentation for methane oxidation activity in surface crusts comes from incubation studies with mixed and intact surface crust samples, but also from experiments with ^{13}C-labeled methane, which showed a 23–36% recovery of the label in carbon dioxide.[16]

The practical implication of these observations is that oxidation of methane during passage through the surface cover will mitigate emissions to the atmosphere. In rice fields more than 90% of the methane produced in deeper soil layers may be reoxidized before escaping to the atmosphere.[19] Currently, however, little is known about the importance of this process under manure storage conditions. A French seasonal study of GHG emissions from cattle slurry tanks with a natural surface crust[20] found net emissions of 28–31 $g\,CH_4\,m^{-2}\,d^{-1}$. In comparison, the greatest potential for methane oxidation in surface crusts observed so far[17] averaged 4.5 $g\,CH_4\,m^{-2}\,d^{-1}$. These results indicate that research and development to optimize storage conditions should be pursued to achieve more efficient control of methane emissions, but due attention must be given to emissions of nitrous oxide, the other potent GHG.

Nitrous oxide is an intermediate of two microbially mediated nitrogen transformation processes. Nitrification is an aerobic process that converts ammonia to nitrite and nitrate, whereas denitrification is an anaerobic process that reduces nitrate and nitrite to nitrogen gas. Often these processes are tightly coupled at aerobic–anaerobic interfaces. In the organic-rich environment of livestock slurry, the oxygen-dependent production of nitrite and nitrate is restricted to liquid–air interfaces, i.e., at the surface of an uncovered slurry store or near air-filled pores connected to the atmosphere in surface crusts and covers. The slurry is rich in ammonium and, depending on diffusional constraints, nitrification in surface crusts may be intense and result in very high concentrations of nitrite and nitrate.[15] Diffusion of nitrite and nitrate into anaerobic zones would then fuel denitrification. Nitrous oxide, which is an intermediate of both reactions, could be lost from the system. To further complicate the picture, accumulation of nitrite may trigger nitrous oxide production via a different process, nitrifier denitrification, which is carried out by aerobic ammonium-oxidizing bacteria.[21] Also, a microbial pathway called anammox, which stands for anaerobic ammonium oxidation,[22] has been described in wastewater treatment plants and natural environments. Finally, an abiotic anaerobic ammonium conversion to nitrogen gas[23] could participate in nitrogen transformations and N losses in slurry storage systems. The relative contribution of these various pathways to the emission of nitrous oxide in slurry stores has not been determined.

Initial experiments using the microbial biomass attached to mature artificial semi-permeable geotextile covers from swine lagoons demonstrated a high rate of nitrifying and denitrifying activity (Fig. 1). Significant potentials for nitrifying and denitrifying activity were observed only with mature (>3 years old) geotextile cover samples. Field tests of the effectiveness of artificial covers demonstrate that volatile organic compounds, ammonia, and hydrogen sulfide emissions can be reduced by up to 80%.[14,24] The presence of specific groups of nitrifying and denitrifying bacteria indicates that microbial transformations enhance the ammonia emission control provided by the physical barrier of the cover. From a US perspective, limiting ammonia and volatile organic compound emissions is paramount, but it is important to emphasize that in the process nitrous oxide may be emitted. From a GHG emission perspective, balancing any additional nitrous oxide emission with reduced methane emissions would be very important.

EFFECT OF SURFACE COVERS ON GHG EMISSIONS

Little is presently known about the influence of surface covers on emissions of methane, nitrous oxide or other gases from livestock slurry stores. There are strong seasonal patterns in GHG emissions associated with fluctuating climatic conditions. In a pilot-scale study of cattle slurry tanks, an inverse relationship was observed between surface crust moisture and nitrous oxide emissions during summer storage.[9] Drying periods could extend the volume of the surface

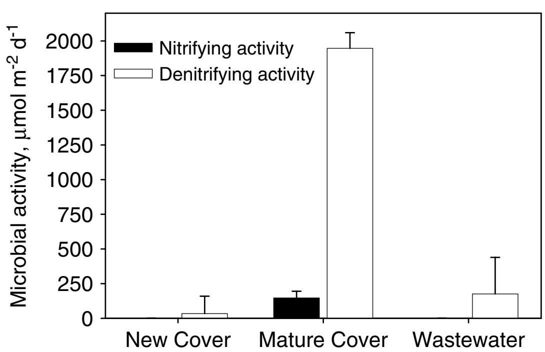

Figure 1. Rates of aerobic nitrifying and anaerobic denitrifying activity associated with lagoon geotextile cover samples and underlying wastewater from a swine lagoon (n = 3). Comparisons were based upon a 0.5 cm thick layer. Source: DN Miller (unpublished).

crust where conditions are suitable for nitrification and denitrification, and further, the evaporation of water may increase ammonium concentrations in micro-sites to a level that triggers nitrifier denitrification via nitrite accumulation.

Methane oxidation is inhibited by ammonia, which can reach high concentrations in livestock slurry and surface covers. Nitrite and nitrate were present in the surface crust samples where methane oxidation was demonstrated, which shows that both ammonium oxidation and methane oxidation had occurred.[15] Since surface covers are characterized by strong chemical gradients, diffusional constraints may well result in the development of very different living conditions over short distances, but additional research needs to be conducted to determine whether a co-oxidation mechanism or distinct populations of ammonium and methane oxidizing bacteria are responsible.

NEW STORAGE CONCEPTS

It is probable that fluctuating environmental conditions alter GHG emissions from livestock slurry stores by affecting the activities of microorgansims in the surface covers. Nitrous oxide production reflects an imbalance between different enzymatic reactions, and changes in oxygen status, for example in connection with rainfall or drying phases, or accumulation of nitrite and nitrate, can lead to high emissions.[25] Methanotrophic bacteria need oxygen, and fluctuating moisture conditions in a surface cover presumably shift the position where living conditions are optimal for these organisms, thereby retarding growth and activity. Accordingly, we suggest that stabilizing the environment of surface covers with respect to physical and chemical gradients would promote the development of a microbial community that is adapted to exploit the resources (electron donors and electron acceptors) available. Thus, a more stable environment could reduce emissions of nitrous oxide, as well as stimulate the consumption of methane and other products of the anaerobic processes in the stored slurry, including malodorous compounds.

Currently new storage concepts for reduction of GHG and odor emissions are being evaluated.[26] In one concept, a biologically active surface cover is combined with an additional vented cover. Adding a vented cover would reduce variations in micro-climatic conditions in the biologically active surface cover while maintaining aerated conditions inside the storage. The longer residence time of gases emitted from the slurry would also yield higher steady-state concentrations, which in turn could stimulate microbial growth and increase the consumption of nitrous oxide, methane or other gases in the surface cover. In initial studies, increasing headspace methane concentrations indeed stimulated methane oxidation activity in slurry storage surface crusts.[17] With forced aeration of the storage headspace there is a potential for adjustment of headspace concentrations in order to minimize emissions from the storage.

RESEARCH NEEDS

Critical information is needed in at least three areas in order to develop more effective covers for minimizing GHG emissions.

The first area concerns understanding the structure, activity, and development of the microbial communities in manure storage and treatment systems. What organisms are involved, and how is spatial organization related to different metabolic types? How does the micro-environment affect community composition and activities? How stable are cover microbial communities in a fluctuating environment, and what is the influence of manure type? Certainly a combination of culture-based and molecular microbiology techniques together with process studies using micro-sensors will be needed to answer these questions.

The second area of research should address the effectiveness of surface covers and storage strategies in statistically rigorous ways both in laboratory, pilot and field scales. What is the reduction potential for each of the gases (methane, nitrous oxide, ammonia, odor compounds, hydrogen sulfide) with different types of manure? How do emissions change seasonally and annually? How does climate affect emissions?

The final area of research should focus on improving the technology. Initial steps examining the use of double covers are being made, but other improvements will likely be suggested by results obtained in the other two identified research areas. The ultimate goal, of course, is a reliable, cost-effective storage concept that is easily adapted to a variety of sites.

Progress in all three proposed research areas need to be made in order to develop a reliable working technology for livestock producers. Advances in one area will likely affect approaches and technology adopted in other research areas in order to achieve optimum effectiveness of bioactive covers. Internationally agreed environmental regulations, as well as public support for implementation of technology to minimize the environmental impact of livestock production, will be important drivers for continued research and development.

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